Description of the Meteorological Model Used to Estimate ^{131}I Depositions Per Unit Area of Ground in the Absence of Environmental Radiation Data

Contents

In the absence of environmental radiation monitoring data, a meteorological model was used to estimate the ^{131}I depositions per unit area of ground. The meteorological model consists of three parts:

- Determination of the source term: ^{131}I activity released into the atmosphere and initial distribution of ^{13l}I within the stem and the mushroom of the radioactive cloud.
- Modeling of the transport and dispersion across the United States of the ^{13l}I present in the radioactive cloud.
- Determination of the fraction of the airborne ^{131}I activity that is scavenged to the ground with precipitation (the model does not calculate dry deposition).

Thus, the amount and vertical distribution of radioactivity is first estimated. This radioactivity is then carried across the country with the winds. Finally, when the spreading cloud encounters precipitation, a fraction of the radioactivity in the overhead column is deposited with the rain or snow.

The transport and dispersion model contains many simplifications. While intuitively more realistic and sophisticated models simulate the atmospheric processes better, they also demand more input information which is often unavailable and have the potential to introduce grossly erroneous as well as better predictions. It should be noted that the meteorological model has been used to reconstruct fallout for only nine of the 90 tests that were analyzed, and that these nine tests represent only 8,100 kCi out of the 150,000 kCi of ^{131}I released to the atmosphere in the NTS. Further, attempts were made to include a few more realistic features in other transport and dispersion models. The calculations of deposition from these "better" models were compared with the measured deposition from several tests and were found not to be significantly better than the simpler model described below.

A1.1. ATMOSPHERIC RELEASE AND INITIAL DISTRIBUTION OF ^{1311} IN THE RADIOACTIVE CLOUD

A1.1.1. Atmospheric Release of ^{131}I

The radioactive cloud that was formed after an atmospheric detonation near the ground surface usually was in the shape of a mushroom with a stem extending from the mushroom cloud base to the ground. The radioactive cloud could penetrate to the highest layers of the troposphere, and occasionally reached into the stratosphere.

The ^{131}I activity released into the atmosphere, Q in Ci, for a given nuclear test detonated at time, H, can be derived for most tests from data in Hicks (1981a) and calculated, in an indirect fashion, as:

$$Q(H) = \frac{DEP(H)}{BF} \qquad (A1.1)$$

where:

BF is the bomb fraction per square meter, as given in Hicks (1981a), and

DEP(H) is the local deposition of ^{131}I per square meter at the time of detonation, H, expressed in Ci m^{-2}, corresponding to an exposure rate of 1 mR h^{-l} at H + 12 hours.

Data in Hicks (1981a) also allow the calculation of the activity of ^{131}I present in the environment at time, T, after detonation, Q(H+T), according to:

$$Q(H+T) = \frac{DEP(H+T)}{BF} \qquad (A1.2)$$

As shown in *Table 2.3* and in *Figure 2.3* of **Chapter 2**, the activity of ^{131}I that is found in the radioactive cloud or on the ground after a nuclear test results not only from the production of ^{131}I itself but also from the decay of its precursors (^{131m}Te, ^{131}Te, and, to a lesser extent, ^{131}Sb). The activity of ^{131}I released into the environment at the time of the nuclear test does not, therefore, represent the "total" activity of ^{131}I that will be found 1 or 2 days later, which is the quantity of interest in this study. In order to take into account the contribution that these precursors eventually will make to the activity of ^{131}I, the activity of ^{131}I at the time of detonation was calculated as if all precursors had already decayed into ^{131}I. The activity obtained is called "total" activity of ^{131}I released into the environment and is denoted as Q* in this report.

The value of Q* for a given test was obtained as follows. First, the activity of ^{131}I present in the environment, Q(H+T), was calculated for a time, T, after detonation large enough that all the precursors of ^{131}I had decayed to negligible levels. Second, that activity was extrapolated back to the time H of detonation using the law of radioactive decay.

The value of Q(H+T) was calculated for T = 10 days from *equation A1.2* and the value of Q* was calculated as:

$$Q^* = Q(H+T) \times e^{\lambda_r \times T} \qquad (A1.3)$$

where:

λ_r is the radioactive decay constant of ^{131}I, expressed in d^{-1}.

The value of DEP(H+T), with T = 10 days, was reported by Hicks (1981a) for all shots that resulted in off-site detection of radioactive materials. However, the value of BF was reported for all above-ground tests and for two cratering shots only (Danny Boy and Sulky). For the cratering shots for which BF was not provided by Hicks (1981a), use was made of the total activity releases, TR, that were provided in Hague (1979) for all cratering shots. As it was observed that the product BF x TR is similar for Danny Boy and Sulky, the mean value of BF x TR for those two cratering shots was divided by the relevant value of TR to estimate the value of BF for all other cratering shots. As will be discussed in **Section A1.3,** the uncertainty in the value of BF is not deemed to contribute substantially to the overall uncertainty.

Table A1.1. Apportionment of the ^{131}I activity produced according to the type of test.

Fraction of ^{131}I in each category			
Type of test[a]	Cloud top	Cloud stem	Local deposition[b]
Surface or Tower	0.8	0.1	0.1
Balloon or Airdrop	0.9	0.1	0.0

[a] For crater or underground tests the cloud did not have a mushroom shape. It was assumed that 100% of the ^{131}I activity released into the atmosphere was available for transport and dispersion by the wind, usually at 3.1 km altitude.

[b] Local deposition refers to that deposition of radioactivity which occurs within the first few hundred km of the point of detonation and which usually results from the settling of larger particles of the radioactive cloud.

The activity released into the atmosphere by underground shots that vented also has been reported by Hicks (1981b).

The activity released into the atmosphere is equivalent to the total activity produced in a test conducted above ground but may be substantially less in a cratering or in an underground test. The activity of "total" ^{131}I released into the atmosphere, normalized per unit of fission yield, was on average, about 0.14 MCi kt^{-1} for the above-ground shots. The values of Q* for all tests for which data are available are presented in *Tables 2.1* and *2.2* in **Chapter 2**.

A1.1.2. Initial Distribution of ^{131}I in the Radioactive Cloud

The apportionment of the amount of ^{131}I between the mushroom cloud and the stem was estimated by Ferber (1986)[1] according to the type of nuclear test as given in *Table A1.1.*

The initial partitioning of ^{131}I for one test (Simon) is shown in *Figure A1.1* where 10% of the ^{131}I has been subtracted for local fallout. The initial distribution, as illustrated in *Figure A1.1,* was not measured in any NTS test.

After the radioactive cloud stabilizes following the detonation, the larger particles fall and are carried horizontally by the winds. Those particles which fall rapidly enough to reach the ground as local deposition have been measured by their gamma radiation from the ground by exposure meters. Each of these rapidly falling particles reaching the ground has a trajectory which depends upon its height of origin in the cloud, size (or fall speed), and the horizontal wind in the layer through which the particle falls. Because the wind speed and direction (measured at or near the time of detonation at the NTS) varies with altitude, virtually every particle possesses a unique trajectory ending up on the ground occupied only by particles of about the same size and altitude of origin. Alternatively, if one measures the radioactivity of the ground in a given spot, the radioactivity must have come from only one altitude in the stabilized cloud. Further, the size of the particle need not be measured because there was only one fall speed that could have traced the particle's path from a specific point on the ground back to its origin in the cloud. However, particles of several sizes may originate from the same altitude layer but they will deposit in different ground locations.

The distribution of radioactive particles in a stabilized radioactive cloud and the amount of all large particles in a given layer may thus be reconstructed from NTS winds and local fallout measurements from exposure readings. It is assumed, in the absence of better information, that the vertical distribution of ^{131}I in the cloud given in *Table A1.1.* is the same as the radioactivity of the larger particles which are measured in the local deposition. The uncertainties in this reconstruction and its variability from test to test does not justify the breakdown of the ^{131}I into segments beyond the three given in the table.

A1.2. TRANSPORT AND DISPERSION

The transport and dispersion of the radioactive cloud has been calculated for each important atmospheric and vented nuclear test using routine upper air weather charts which depict airflow along surfaces of constant air pressure which are approximately horizontal surfaces. These standard charts, provided twice a day by weather services for their routine weather predictions, were used to construct horizontal trajectories, or paths, of air parcels (List 1953, 1954, 1956; Machta et al. 1957; NY0 1952, 1954) that originated at the Nevada Test Site at the time of each detonation and that moved across the United States between altitudes of about 3 and 12 km above mean sea level (MSL). Air parcels were carried along isopleths of airflow (streamlines) appearing on each 12 hourly weather map (00 and 12 GMT) at speeds which are given by the weather maps. The initial trajectory starts at the NTS at detonation time and is carried along the streamlines of the map closest in time until the next 06 or 18 GMT time. Thereafter, the segments start where the previous segment left off and carried for additional 12-hourly intervals. The 6-hourly positions are found by interpolation. Trajectories for all tests in this report except Sedan, Little Feller I, Des Moines, Bandicoot, Pin Stripe, Schooner, Johnie Boy, Small Boy, and Baneberry were prepared during the period of the tests; trajectories for these tests were calculated for this report at standard altitudes to which the radioactive cloud rose.

[1] Ferber, G. NOAA/Air Resources Laboratory, Silver Spring, MD 20892. Personal communication (1986). The method used by Ferber is explained later in *Section A1.1* from the measurements of local fallout and the NTS winds.

Figure A1.1. Schematic depiction of the mushroom cloud and stem resulting from the test Simon, detonated April 25, 1953.

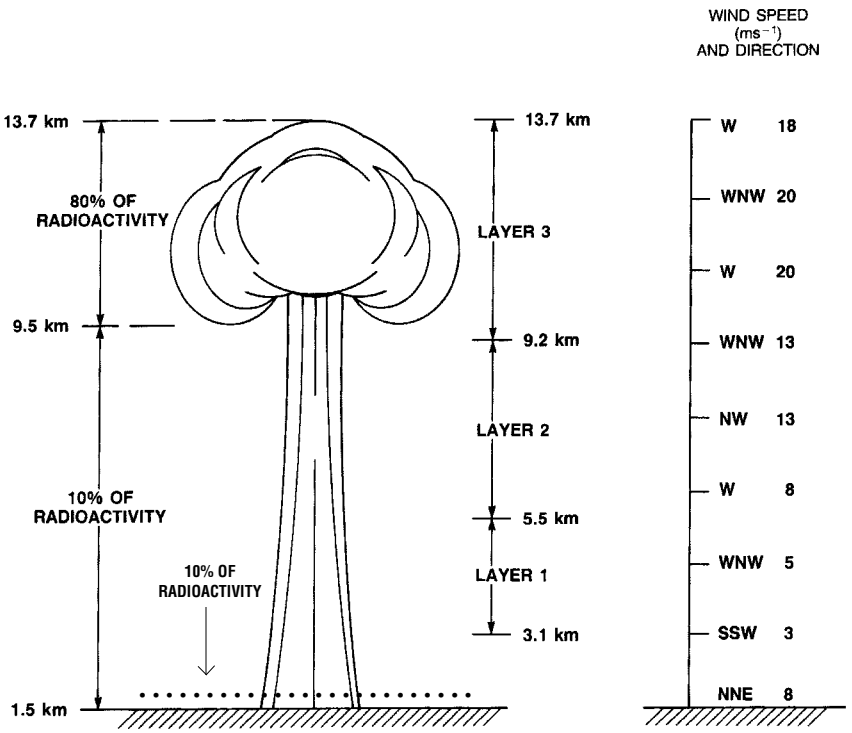


Figure A1.2 is an example of such trajectories at four of the standard levels (usually 3.1, 5.5, 9.2 and 12.2 km above mean sea level) where the successive positions of air parcels at each altitude are indicated every 6 hours. In general, the trajectories at various elevations diverged in both direction and forward distance after leaving the test site. For example, the calculated position of the radioactive cloud after about 36 hours after detonation or at 00 GMT, 27 April 1953 for test Simon appears on *Figure A1.3* based on the trajectories seen on *Figure A1.2*. The center of the cloud at 3.1 km altitude was located over western Wyoming while the cloud center at 5.5 km was over northern New Mexico. However, there was radioactivity at all altitudes between 3.1 and 5.5 km. At the mid-altitude of 4.3 km, the cloud center was assumed to lie midway along the line joining the connected points on the two trajectories labelled "27" (for 00 GMT, 27 April), or over west central Colorado. At every other altitude between 3.1 and 5.5 km, the position of the cloud center can be similarly interpolated along the line.

In addition the cloud has grown by atmospheric turbulent diffusion at an assumed rate of 7.4 km h^{-1} based on the spread of smoke puffs and other tracer clouds (Heffter 1965). At each level in the atmosphere, after 36 h the cloud is assumed to be a circular disc with a radius of 266 km (7.4 km h^{-1} x 36 h). The size of the initial cloud at the time of stabilization is considered to be negligibly smaller compared to the size of the cloud after many hours of transport and atmospheric diffusion. The elongated shaded area presents the projection of all the discs to the ground; it shows where the model calculates the cloud to be overhead.

The layer between 3.1 and 5.5 km lies within the stem of the cloud from test Simon. The total release of ^{131}I from test Simon was reported as 6,250 kCi and 10% or 625 kCi were assigned to the stem of the cloud. The base of the stem is the ground at 1.5 km msl and, from local observations, the top of the stem or the base of the mushroom head was 9.5 km msl. The 625 kCi were uniformly distributed over the 8 km (9.5 km-1.5 km) yielding about 78 kCi for each km of altitude in the stem. Since the lowest trajectory started at 3.1 km rather than 1.5 km, this small amount of ^{131}I in the layer 1.5 to 3.1 km was also assigned to local or close-in fallout. Note that many nearby mountains reach well above 1.5 km downwind of the NTS. Thus, in the layer between 3.1 and 5.5 km or a layer 2.4 km thick, there were about 190 kCi (78 kCi km^{-1} x 2.4 km). This much ^{131}I lies in the shaded area between New Mexico and Wyoming at 00 GMT 27 April 1953 according to the model calculations.

If it rained or snowed anywhere in the shaded area, the model deposits a small fraction of the activity directly overhead as described later. Rainfall information is available only for 24-h periods. It is not known during which of the four periods of a day the rain or snow may have scavenged the radioactivity from the nuclear cloud. (The position of the cloud given by the shaded area is calculated each 6 hours). It is assumed that the rain or snow occurs continuously during the 24-h period. Finally, one must note that the concentration of ^{131}I is the same everywhere in the shaded area between New Mexico and Wyoming. The uniformity applies individually to all segments between the altitudes at which the trajectories are computed.

Figure A1.2. Paths of the trajectories followed by portions of the radioactive cloud at the altitudes of 3.1, 5.5, 9.2, and 12.2 km above mean sea level (MSL) resulting from the test Simon detonated 25 April 1953. The closed dots represent the locations of the trajectories at 00:00 GMT, while the numbers near the closed dots are the day of the month. The open dots represent the locations of the trajectories at 06:00, 12:00 and 18:00 GMT.

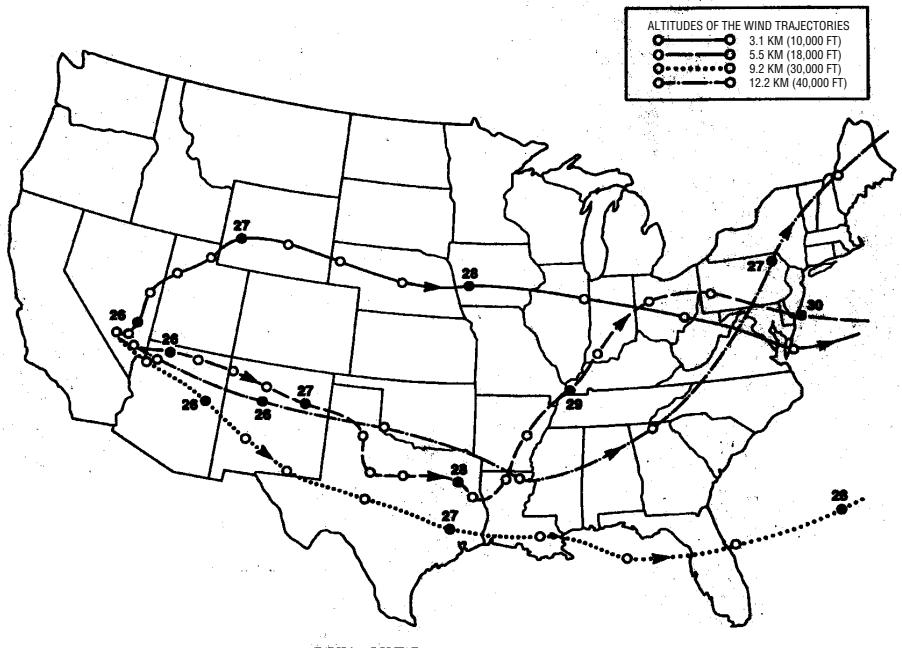
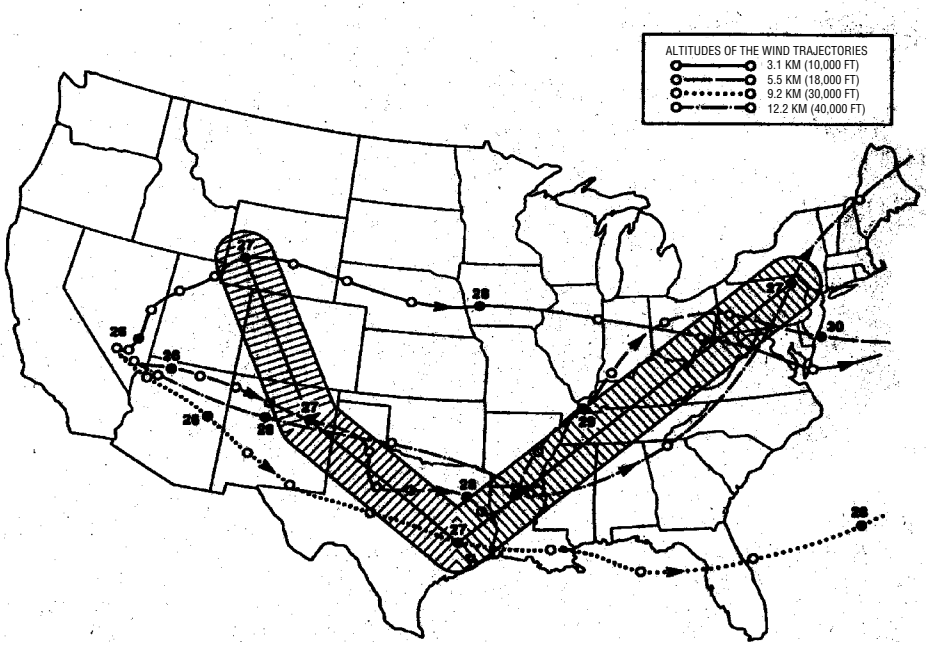


Figure A1.3. Outline of the meteorological reconstruction of the entire Simon nuclear cloud 36 hours after detonation.



The Simon cloud rose initially to heights above 5.5 km. The centerline of the segment of the cloud between 5.5 and 9.2 km lies between northeastern New Mexico and southeastern Texas, again joining the points labeled "27." The line from southeastern Texas and northeastern Pennsylvania shows the centerline position between 9.2 and 12.2 km heights of the topmost trajectory altitude, even though it was observed to rise to 13.8 km, which is in the stratosphere. At an altitude of 10.7 km, the mid-point between 9.2 and 12.2 km, the center of the cloud would be over northern Tennessee in the shape of a disc with a radius of 266 km as in the lower levels. The concentration in each disc at each altitude is assumed to be uniform.

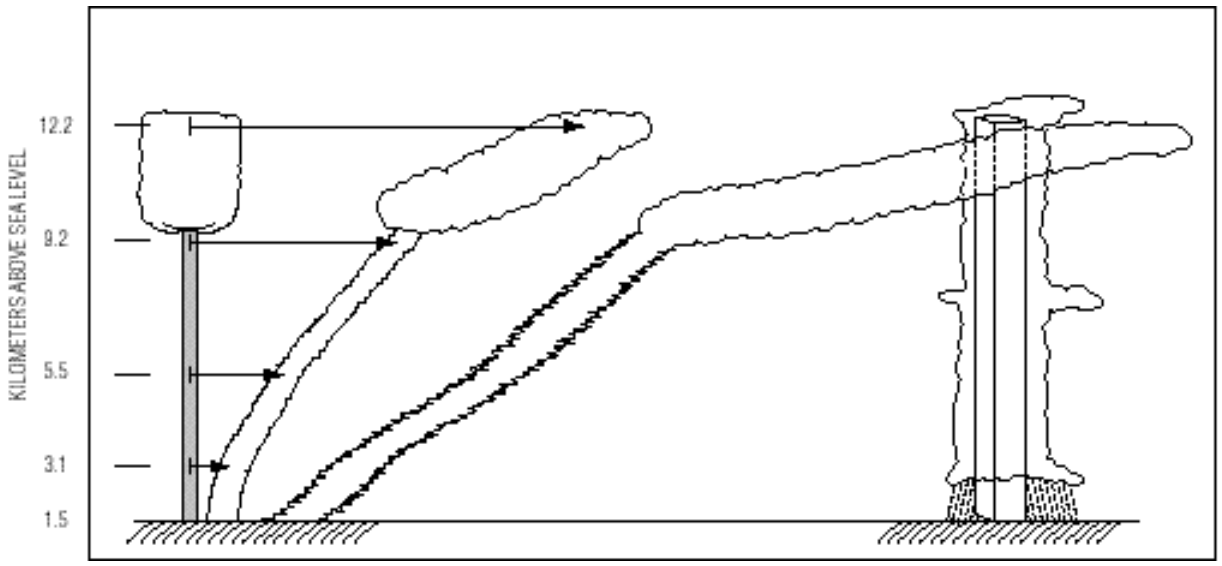
Note that the cloud between 9.2 and 12.2 km is especially strongly sheared by the winds, that is, the end points are far apart. This means that the radioactivity in that segment is spread over a much larger area than is the case at lower altitudes. The amount of radioactivity in a vertical overhead column, the quantity used in precipitation scavenging is reduced by the strong shear. The stretching of an initially vertical column of a nuclear cloud by winds is illustrated schematically in *Figure A1.4* at two successive times. This picture reflects only the change with height of the wind speed, the more common mode of wind shear, but shear due to winds blowing in different directions at successive altitudes also occurs. A weather cloud is shown intersecting the nuclear cloud at the second position.

The total amount of ^{131}I initially released into the atmosphere remains nearly constant during the few days before the cloud moved beyond the borders of the U.S., as only a small fraction of the ^{131}I has time to decay and as the depletion due to deposition processes is relatively small. The empirically derived wet scavenging coefficients remove only a few percent of the overhead cloud radioactivity each day with normal rainfall, as seen later in *Table A1.2*.

The above described method for treating the radioactive cloud following detonation is called the "transport and dispersion model."

As the radioactive cloud was carried over the U.S. by the upper winds, fallout could be expected beneath it, especially if precipitation were involved. During some of the period of nuclear testing, gummed-film samplers were distributed over the U.S. and exposed for 24-h periods and could be compared with predictions of the cloud transport and dispersion model. The fraction of the calculated cloud content deposited on the ground varied greatly. Further, sometimes depositions occurred where no cloud was predicted to be overhead especially for cases after the radioactive cloud was predicted to have moved away from the area. This residual contamination has also been found for other trace substances in the air; after a puff-type "pollutant" has been carried away by stronger upper-level winds, measurable deposition frequently occurs for a few days (Draxler 1987, 1988; Segal et al. 1988). Some discrepancies were resolved by calculating additional trajectories below 3.0 km. When the meteorological model was applied to tests for which there were deposition measurements, the errors were large.

Figure A1.4. Schematic representation of stretching of the nuclear cloud caused by increasing wind speed with height. The cloud shown at time of detonation, at the left, and at two time intervals later. The time-dependent widening of the cloud is also indicated. A schematic unit column used for calculating the cloud's radioactive content is shown intercepting a portion of the highest layer of the cloud.



It must be recognized that estimates of the overhead ^{131}I column content by the above method depend both on the accuracy with which the model initially distributes ^{131}I in the radioactive cloud and on the meteorological transport and dispersion assumptions and calculations. These include also the uncertainties that exist because actual air parcel trajectories are not constrained to the constant pressure surfaces which are quasi-horizontal.

A1.3. DEPOSITION OF ^{131}I

A distinction is usually made between two physical processes producing deposition of radioactive materials to the ground: wet deposition (with falling precipitation) and dry deposition (without precipitation). In the western U.S., most of the deposition of ^{131}I was dry because the area is typically drier than the eastern part of the country and because special efforts were made to avoid detonations when precipitation was present in the region. Experience indicated that rain greatly enhanced the amount of radioactive materials that was deposited from the nuclear tests; hence in the eastern U.S. (generally east of the Rocky Mountains), where rain is more frequent, the largest depositions occurred with rain (Beck et al. 1990). For any one test, the amount of ^{131}I deposited generally increased with the amount of rainfall. Dry deposition, on the other hand, depends upon the concentration of ^{131}I in the air at ground level, low altitude atmospheric turbulence, the nature of the surface upon which the dry deposition occurs, and the chemical and physical form of the ^{131}I.

A1.3.1. Wet Deposition

The amount of ^{131}I that was deposited per unit area of ground with falling precipitation in a given day, DG_{wet} was obtained as:

$$DG_{wet} = A_{cl} \times SC \qquad (A1.4)$$

where:

A_{cl} is the activity of ^{131}I present in the radioactive cloud in a vertical column of unit area during the day considered, and

SC is the scavenging coefficient, which represents the fraction of the activity present in the cloud which is removed with falling precipitation during that day.

The value of the scavenging coefficient depends, among other factors, upon the amount and intensity of rain, on the respective altitudes of the rainfall and radioactive clouds, and on the physical and chemical forms of ^{131}I in the radioactive cloud. Most of the information that would be necessary to estimate the value of the scavenging coefficient for a given day and a given area is usually not available. It is possible, however, to obtain the distribution of the average scavenging coefficients as a function of the precipitation index value (see *Table 3.2,* **Chapter 3**) for tests for which estimates of ^{131}I deposition were derived from gummed-film data. For that purpose, the cloud transport model was used to calculate the values of A_{cl} corresponding to 14 tests which were found in the analysis of gummed-film data to have resulted in relatively important depositions of ^{131}I with falling precipitation in the country. In *equation A1.4,* DG_{wet} was obtained from the gummed-film data, A_{cl} was taken from the cloud transport model, and SC, as the only unknown, could be calculated. *Table A1.2* shows the distribution of the SC values obtained for the 14 tests as a function of precipitation indices greater than 2. Although the table exhibits very wide variability of the scavenging coefficient for each precipitation index, with GSDs ranging from 5 to 10, a general increase in the mean scavenging coefficient with higher index numbers is demonstrated.

Table A1.2. Estimates of wet scavenging coefficients obtained for 14 nuclear tests as a function of the precipitation index.

Precipitation index	Scavenging coefficients[a]		
	Geometric mean	GSD	Number of cases
2	0.013	8.5	93
3	0.013	10.0	69
4	0.020	7.6	79
5	0.020	7.4	74
6	0.058	6.9	84
7-9	0.17	5.2	34

[a] The fraction of the overhead radioactivity deposited per day

Stratification of the scavenging coefficients for available factors other than the precipitation index value, such as the height of the layer of the atmosphere containing the radioactive debris, failed to reduce the variability. Some intuitively important factors, such as the height above the ground at which natural clouds might scavenge the radioactive cloud, were not available. The very large variability of the scavenging coefficient reflects all of the uncertainties in both the radioactive cloud and in the gummed-film measurements as well as other factors such as the uncertainty in the amount of ^{131}I released into the atmosphere, the imperfect coincidence between time of the predicted cloud passage, time and location of the precipitation event, and defects in the gummed-film samples and analyses.

The scavenging coefficients of *Table A1.2* were used to estimate wet deposition for those tests where gummed film was not deployed. It was assumed that, for a given precipitation index, the appropriate coefficient used to predict the wet deposition would have the same GSD and associated uncertainty as it had in the 14 nuclear tests. The uncertainty of the scavenging coefficient would be considered to also be the estimated deposition uncertainty for the model calculations.

A1.3.2. Dry Deposition

Dry deposition of ^{131}I is usually assumed to be related to the concentration of ^{131}I in ground-level air. The transport and dispersion model that is used in this report for nine tests does not allow for the prediction of concentrations of ^{131}I in ground-level air. Consequently, it is not possible to predict the dry deposition of ^{131}I with this method and it is unaccounted for in the analysis of the nine tests by the transport and dispersion model. It should be pointed out, however, that dry deposition is considered in the analysis of the other 81 tests.

REFERENCES

Beck, H. L.; Helfer, I. K.; Bouville, A.; Dreicer, M. Estimates of fallout in the continental U.S. from Nevada weapons testing based on gummed-film monitoring data. Health Phys. 59(5):565-576; 1990.

Draxler, R. R. One year of tracer dispersion measurements over Washington, D.C. Atmos. Environ. 21(1):69-77; 1987.

Draxler, R. R. The persistence of pollutants downwind of a point source following termination of the emission. Boundary Layer Meteor. 42:43-53; 1988.

Hague. Copy of a letter sent to Andre Bouville by David Wheeler; 1979.

Heffter, J. L. The variation of horizontal diffusion parameters with time for travel periods of one hour or longer. J. Appl. Meteor. 4(1):153-156. 1965.

Hicks, H. G. Results of Calculations of External Gamma Radiation Exposure Rates from Fallout and the Related Radionuclide Compositions. Lawrence Livermore Laboratory Report UCRL-53152, Parts 1-S; 1981a.

Hicks, H. G. Radiochemical Data Collected on Events from which Radioactivity Escaped beyond the Borders of the Nevada Test Range Complex. Lawrence Livermore National Laboratory Report UCRL-52934; 1981b.

List, R. J. Radioactive Debris from Operations Tumbler and Snapper, Observations Beyond 200 Miles from the Test Site; Parts I and II (declassified with deletions in April 1959). Joint U.S. Atomic Energy Commission/U.S. Weather Bureau Reports NYO-4505 (del), NYO-4512(del), February 1953.

List, R. J. The Transport of Atomic Debris from Operation Upshot-Knothole (declassified with deletions in April 1959). Joint U.S. Atomic Energy Commission/U.S. Weather Report NYO-4602 (del), June 1954.

List, R. J. Radioactive Fallout in North America from Operation Teapot (declassified with deletions in April 1956). Joint U.S. Atomic Energy Commission/U.S. Weather Bureau Report NYO-4696 (del), February 1956.

Machta, L.; Hamilton, Jr., H. L.; Hubert, L. F.; List, R. J.; Nagler, K. M. Airborne measurements of atomic debris. J. Meteor. 14:165-175; 1957.

NYO. New York Operations Office. Radioactive Debris from Operations Buster and Jangle, Observations Beyond 200 Miles from the Test Site (declassified with deletions in April 1959). U.S. Atomic Energy Commission Report NYO-1576 (del), January 1952.

NYO. New York Operations Office. Radioactive Debris from Operation Upshot and Knothole (declassified with deletions in April 1959). U.S. Atomic Energy Commission Report NYO-4552 (del), February 1954.

Segal, J., Yu, C. H.; Arritt, R. W.; Pielke, R. A. On the impact of valley/ridge thermally induced circulations on regional pollutant transport. Atmos. Environ. 22(3):471-486; 1988.